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Implementing miscanthus into farming systems: A review of agronomic practices, capital and labour demand

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A R T I C L E I N F O

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A B S T R A C T

Miscanthus is a promising bioeconomy crop with several biomass utilisation pathways. However, its current cultivation area in Europe is relatively low. This is most likely due to a lack of knowledge about the implementation of miscanthus into farming systems. This study reviews current best practices and suitable land areas for miscanthus cultivation. Biomass production costs and labour requirements were evaluated over the whole 20-year cultivation cycle of four utilisation pathways: combustion, animal bedding, and both conventional and organic biogas production. The assessment was performed for two field sizes (1 and 10 ha), two average annual yield levels (15 and 25 t dry matter ha^{-1}), and both green and brown harvest regimes.

The maximum attainable annual gross margins are 1657 € ha^{-1} for combustion, 13,920 € ha^{-1} for animal bedding, 2066 € ha^{-1} for conventional and 2088 € ha^{-1} for organic biogas production. The combustion pathway has the lowest labour demand (141.5 h ha^{-1}), and animal bedding the highest (317.6 h ha^{-1}) due to additional baling during harvest.

Suitable cultivation areas include depleted soils, erosion-prone slopes, heavy clay soils and ecological focus areas such as riparian buffer zones and groundwater protection areas. On such sites, miscanthus would (i) improve soil and water quality, and (ii) enable viable agricultural land utilisation even on scattered patches and strips.

Due to its low demands and perennial nature, miscanthus is suitable for sustainable intensification of industrial crop cultivation in a growing bioeconomy, benefiting soil and water quality, while providing large amounts of biomass for several utilisation pathways.

1. Introduction

The growing bioeconomy aims to replace fossil by biobased resources [1,2], enabling the production of both energy and products from biomass, including that of industrial crops, in the near future [3]. The cultivation of industrial crops needs to be performed in an economically viable but at the same time socially and ecologically sound manner [1]. Ecological cultivation criteria include a low demand for fertilizer, plant protection and energy inputs, a low erosion potential and a positive effect on biodiversity [4,5]. Social criteria include 1) adapting crop selection to local demands thus reduces transport requirements; 2) avoidance of irrigation to maintain water availability; and 3) improvement of public perception of the countryside [4,6]. Perennial crops in particular are predestined to meet those criteria [4,7–9]. Miscanthus (*Miscanthus* × *giganteus* J. M. Greef & Deuter ex Hodk. & Renvoize) is one of the main perennial biomass crops currently grown in Europe [10]. It has great socio-economic potential due to its low demands and high yields [11–16]. It is a rhizomatous perennial C4 grass native to East Asia,

Abbreviations: a, year (*lat. annum*); C, carbon; CH_4, methane; DM, dry matter; EU, European Union; FM, fresh matter; h, hour; ha, hectare; K, potassium; kg, kilogramme; km, kilometre; m^3, cubic metre; Mg, megagramme; N, nitrogen; P, phosphorus; t, tonne.

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which was introduced to Europe during the early 20th century [17,18]. In the past decade, miscanthus has received considerable attention as a multi-purpose crop that can provide large amounts of biomass for the growing bioeconomy in a resource-efficient way [7,10,13].

In the developing renewable energy sector, biomass can be utilized in a number of pathways including combustion, anaerobic digestion and liquid transport fuels [12]. The renewable energy transition is currently progressing, with 27.4% of the primary energy in Europe being produced from renewable resources in 2016 [19]. The EU-28 is the global leader in modern bioenergy production and more than doubled the share of bioenergy in gross final energy consumption between 2000 and 2015 [20]. The generation of electricity from biomass, in particular, increased by 11.0% from 2016 to 2017 [21]. In the EU-28, Germany is the largest producer [21], with biomass providing 23.6% of renewable electricity [22]. This represents 6.9% of the total gross electricity production [23]. This share increased by 82.8% from 2008 to 2018 [24]. Biomass has the major advantage of being a storable energy source which can thus be flexibly deployed [12].

Although perennial crops appear ideal for bioeconomic development, their production currently only plays a minor role in European agriculture [7,15,25]. According to Cosentino et al. (2018) [7], only 43, 800 ha of agricultural land were used for the cultivation of perennial crops in the EU-28 in 2015. Reasons for this include uncertainties about the economic viability and financial returns of novel perennial crops, the long-term allocation of agricultural land to perennial production systems, and the high initial investment costs for establishment [26]. In addition, markets have not yet been established for biomass from perennials, in particular from miscanthus [12,13,15,26]. Hence, there are large uncertainties associated with the economic evaluation of perennial crop production and new ways to market the produce, e.g. via the establishment of agro-cooperatives, need to be created [15,25].

As farmers must manage the resources, capital, land and labour efficiently, the introduction of new crops has to be carefully assessed [27]. In addition to economic considerations, market prices for biomass, opportunity costs [27], and practical and objective information on the establishment, management and harvesting of miscanthus are all crucial to farmers [28–30]. As this information is currently hardly available [26], the establishment of perennial crops is associated with large uncertainties and consequently a relatively high risk [25]. Land availability and land allocation for the establishment of perennial crops is also critical due to the long productive lifetimes of about 20 years for miscanthus and short rotation coppice [15,27], especially when a high proportion of the land is leased [27].

There are currently a number of crucial knowledge gaps on miscanthus cultivation in terms of economic feasibility, biomass marketing, and land and labour management [25]. For this reason, this conceptual study reviews both agricultural practices for successful miscanthus cultivation and the corresponding potential utilisation pathways in order to derive recommendations on how miscanthus can be integrated into farming practices. It assessed the biomass production costs and labour requirements over the entire 20-year cultivation cycle of four utilisation pathways: combustion, animal bedding, and both conventional and organic biogas production.

The study is structured as follows: Material and methods are presented in Section 2. Section 3.1 then summarizes the results of a comprehensive literature review of miscanthus cultivation methods and utilisation pathways. Lands, which can potentially be used to cultivate miscanthus are listed in Section 3.2. This is followed by a detailed cost (Section 3.3) and labour requirement (Section 3.4) evaluation for the four miscanthus utilisation pathways. In Section 3.5, recommendations are derived on how to integrate miscanthus cultivation into practical farming and a final conclusion is given.

2. Materials and methods

Based on the scientific literature, this conceptual study presents current options for miscanthus cultivation for two harvest dates and four biomass utilisation pathways.

2.1. Literature review

A comprehensive, systematic review was conducted of the scientific literature, reports from governmental and non-governmental extension institutions and services, and farmers' magazines, based on the literature database 'Scopus' (Elsevier B.V., Amsterdam, Netherlands) and the search engines 'Google' and 'Google Scholar' (Google Inc., CA, USA). The aim was the structured compilation of information to determine the latest best-practice cultivation steps for miscanthus, including production costs and labour requirements, for the four utilisation pathways: (i) combustion, (ii) animal bedding, (iii) conventional and (iv) organic biogas production. The systematic review followed the steps recommended by Sovacool et al. (2018) [31]. Qualitative (cultivation management) and quantitative (costs, labour requirements) information for the four miscanthus utilisation pathways were collected, structured and summarized.

2.2. Assessment of production costs and labour requirements of miscanthus cultivation

Table 1 provides an overview of the management steps of the four production systems investigated.

The technical cultivation steps for field establishment (1st year), the productive phase 2nd – 20th year) and removal (20th year) vary between the utilisation options in terms of harvest time, harvest technology, crop management and fertilisation regime. Each production system is analysed for two cultivation area sizes: cultivation on 1 ha represents small-scale cultivation, e.g. on patches and strips including test cultivation by farmers and production for self-utilisation; cultivation on 10 ha represents commercial production where the biomass is intended to be marketed. In both cases, a farm-to-field distance of 10 km is assumed to take cultivation on multiple patches/strips and fields into account. All production systems are analysed for two yield levels: 15 t DM ha^{-1} a^{-1} represent a medium yield and 25 t DM ha^{-1} a^{-1} a high yield. Miscanthus is harvested in March for combustion [35] and animal bedding [46]; for anaerobic digestion the optimal harvest date is (mid-) October [33,47]. In the biogas conversion routes, unseparated digestate is used as sole fertilizer, because the digestate is a by-product of biogas production, which can be used very well as fertilizer. In the utilisation pathways combustion and animal bedding chemical fertilizer only is applied, because it is assumed that no digestate from biogas production is available. The biogas route is subdivided into conventional and organic production. Conventional production applies plant protectants and a mulch film in the first year, whereas organic production is based on mechanical weeding only. The organic biogas route was included as a reference for organic miscanthus cultivation, as this production system meets the requirements of the EU Common Agricultural Policy regulations for 'greening' measures, buffer strips next to water bodies and groundwater protection areas (see Section 3.2).

The miscanthus production costs for each utilisation pathway were calculated using the online 'Field Work Calculator of KTBL' [48]. This calculator is frequently used by German farmers to assess and analyse their production system and investigate changes in their crop rotation or machine pool. Field size, farm-field distance, yield level and the cultivation steps for best-practice miscanthus cultivation were entered into the online calculator. The KTBL calculator provided detailed information on average machine costs, working hours and energy demand for each working step. For the depreciation, the interest rate was set at 3% for 3 months. The working hours were subsequently multiplied by the 2018 German minimum wage for full-time (9.25 € h^{-1}) and part-time (8.84 € h^{-1}) agricultural workers [37]. Additionally, the costs for all necessary materials, including rhizomes, fertilizers, plant protectants and mulch film (shown in Table 1), were calculated separately in MSO

Excel 2016.

For each of the four utilisation pathways, the labour requirements for every cultivation step were analysed separately for the 1-ha and 10-ha field size scenario as well as for the medium (15 t DM ha^{-1}) and high yield level (25 t DM ha^{-1}).

In Section 3.4, the findings from the labour assessment of miscanthus cultivation with brown and green harvest are compared to a typical four-year conventional cereal and maize-based crop rotation. This crop rotation included spring barley, winter barley, mustard (intermediate crop), maize, winter wheat, and phacelia (intermediate crop). In order to include a comparison with other perennial crops, the miscanthus pathway *combustion* is compared to poplar short rotation coppice, a common energy crop for combustion [22]. The *biogas* pathway is compared to cup plant, another promising perennial crop for biogas production [49–51], which has recently been approved as a greening measure [52].

3. Results and discussion

3.1. Best-practice miscanthus cultivation for four utilisation pathways

There are a number of energetic and material utilisation pathways for miscanthus biomass. Combustion, ethanol production and anaerobic digestion are three energetic pathways, while animal bedding and lightweight concrete are examples of material end uses [12,34,53].

Combustion is currently the most common utilisation pathway in Europe [54–56]. However, miscanthus is also very suitable as animal bedding material [57]. Compared to conventional straw bedding, miscanthus chips show no difference in terms of cow comfort and cleanliness, cow skin lesions (except for carpus lesions), wasted bedding material and bacterial counts in the cubicles. Indeed, they have a higher water absorption capacity than wood chips and straw [46,55,57,58]. Miscanthus was recently been found to be a promising biogas substrate that can substitute or complement maize. However, for biogas use, miscanthus has to be 'green' harvested in late autumn [32–34,47]. Conventionally, miscanthus is harvested 'brown' after winter when the biomass is dry and most suitable for combustion and animal bedding.

The following sections provide an overview of the miscanthus cultivation steps for conventional (Fig. 1) and organic (Fig. 2) cultivation.

For miscanthus cultivation, first the soil is ploughed and harrowed (in organic farming twice). Then the rhizomes are set using a planter (average planting density 1.5 rhizomes m^{-2} [13,36,38,39] and irrigated using a tank trailer. In conventional farming, weed control is conducted with a soil herbicide [41], then a biodegradable mulch film is applied [42,43]. Once the mulch film begins to decompose, weed control is again conducted. In organic farming, a mulch film cannot be applied, as weed control has to be performed mechanically several times, which would destroy the mulch film. After the first vegetation period, the biomass is mulched. When the miscanthus plants start to regrow, fertilizer (either mineral or digestate) is applied [28,36].

Depending on the utilisation pathway, the biomass has to be harvested green, i.e. before winter, or brown after winter, as each utilisation pathway requires different biomass characteristics and consequently different harvest dates [33]. A 'green' harvest conducted between (mid-) October and early November leads to higher nutrient and moisture contents in the biomass, accompanied by a lower lignin content. A 'brown' harvest after winter in March provides lignified miscanthus biomass with low moisture and nutrient contents. High lignin contents increase the recalcitrance of the biomass [62–64] and thus reduce the efficiency of fermentation processes [65]. On the other hand, higher lignin contents are preferable for combustion, due to the higher heating value of lignin [66]. Brown-harvested miscanthus has a heating value of 17–20 MJ kg^{-1} [11], with low potassium and chloride contents as well as a low ash sintering index, reducing corrosion and fouling of the burning utility [35]. Depending on the harvest date, *miscanthus x giganteus* can achieve dry matter (DM) yields of up to 22 t ha^{-1} when brown-harvested and up to 27 t ha^{-1} when green-harvested in Germany [67]. This difference can be explained by leaf fall over the winter, leading to a yield reduction [33].

The productive harvest phase of miscanthus starts about 3–5 years after its establishment [15,68,69]. In brown-harvest regimes, it is known

Table 1
Overview of assumptions and management steps for miscanthus cultivation for the four utilisation pathways analysed, on which cost and labour requirement calculations are based.

Parameter	Utilisation pathway				References
	Combustion	Animal bedding	Biogas	Organic biogas	
Field Size	1 ha | 10 ha				
Farm-field distance	10 km				
Harvest date	March	March	October	October	[28,32–36]
Harvest process	Chopper	Chopper + baler	Chopper	Chopper	
Yield level	15 t DM ha^{-1} a^{-1} (medium) | 25 t DM ha^{-1} a^{-1} (high)				
Tractor power	102 kW				
Labour costs	Minimum wage: Full-time: 9.25 € h^{-1}/part-time 8.84 € h^{-1}				[37]
Establishment (1st year)	**15,000 rhizomes ha^{-1}**				[13,36,38,39]
Step 1	Soil preparation: plough, harrow				[28,36,40]
Step 2	Weed control: Callisto			harrow and hoe	Type and amount [41]:
Step 3	Rhizome planting (half-automated)				[28,36,40]
Step 4	Watering with manure trailer				[28]
Step 5	Application of mulch film			hoe (4x)	Mulch film [42,43]:
Step 6	Weed control: Callisto, Stomp, Arrat & Dash				Type and amount [41]:
	Mulching				[28,36,40]
Harvest phase (2nd - 19th year)					
Step 1	Soil sampling				
Step 2	Chopper	Chopper + baler	Chopper (incl. silage compaction)		
Step 3	Mineral fertilizer application (N-P-K): medium yield: 52-5-91 high yield: 87-9-152		Digestate application (N-P-K): medium yield: 69-16-160 high yield: 116-27-267		Fertilisation based on nutrient removal: Mineral fertilizer [36]:/digestate [32,33,44,45]:
Harvest & removal (20th year)					
Step 1	Soil sampling				
Step 2	Chopper	Chopper + baler	Chopper		
Step 3	Ploughing (recultivation)				[29]

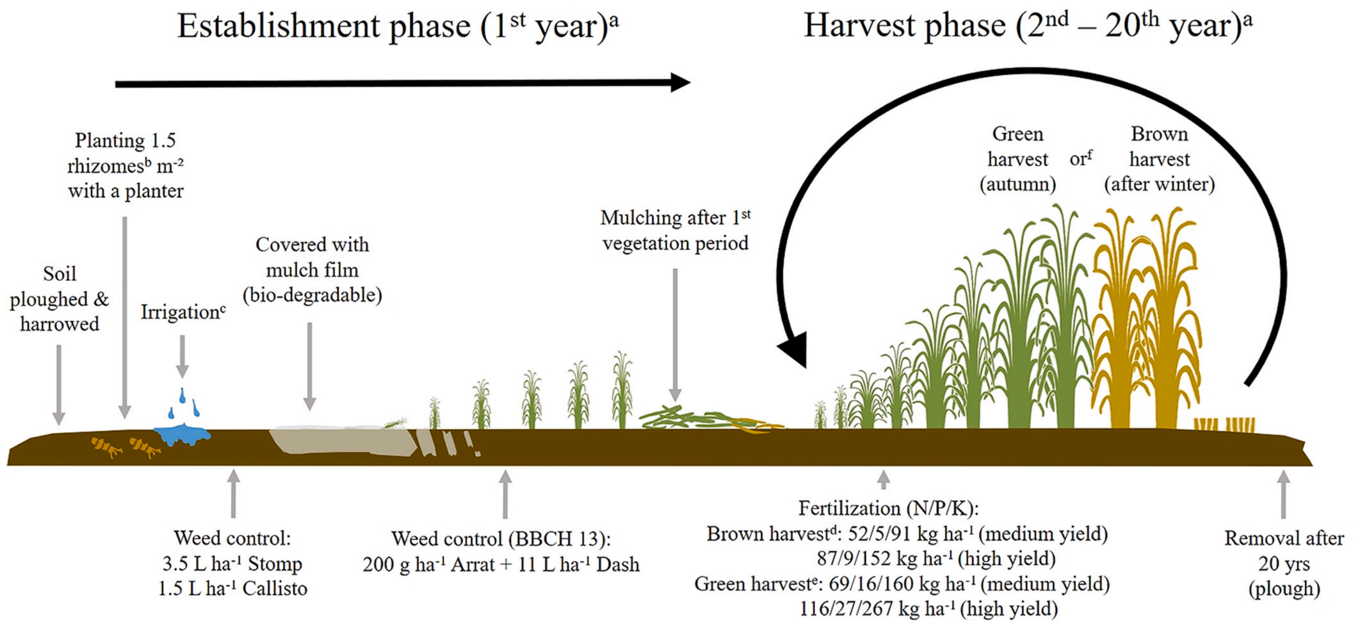

Fig. 1. Schematic overview of the entire miscanthus cultivation cycle for biogas production or combustion from establishment through to harvest and the removal, based on conventional farming practices. [a] = Assuming best-case scenario (low weed pressure, high establishment rate etc.), [b] = 0.5 plants m^{-2} for improved habitat functions, [c] = Depending on weather and soil conditions, [d] = Via synthetic fertilizer. Depending on site-specific conditions (Ø amount based on: [36,59,60], [e] = Via unseparated digestates; Estimated N demand corresponds to average N removal [33,44,61] of 100 kg ha^{-1} (for each digestate application, 70% is available in year of application and 30% in following year). P and K demand cannot be completely met, [f] = Depending on utilisation pathway (e.g. green harvest for biogas production, brown harvest for combustion). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

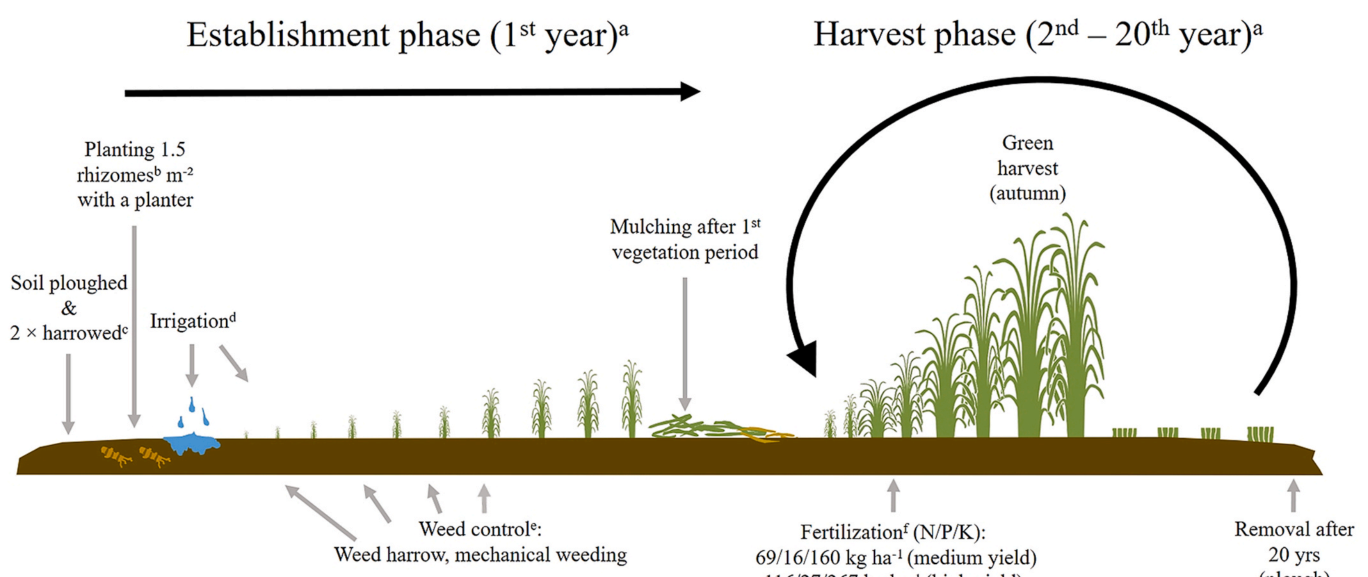

Fig. 2. Schematic overview of the entire miscanthus cultivation cycle for biogas production from establishment through to harvest and removal, based on organic farming practices. [a] = Assuming best-case scenario (low weed pressure, high establishment rate etc.). [b] = 0.5 plants m^{-2} for improved habitat functions, [c] = Disc harrow on large fields (here 10 ha), [d] = Depending on weather and soil conditions, [e] = Depending on weed pressure, [f] = Via unseparated digestates; Estimated N demand corresponds to average N removal [33,44,61] of 100 kg ha^{-1} (for each digestate application, 70% is available in year of application and 30% in following year). P and K demand cannot be completely met.

that miscanthus stands, once successfully established, can be cultivated for a period of 10–22 years [15]. During that time, the nutrients are recycled after senescence via leaf fall and nutrient relocation to the rhizomes, and are then available for resprouting the following year [70]. However, it is not known whether the same lifetime can be achieved with the green harvest regime. This uncertainty about the long-term productivity of the crop, when harvested green before senescence, can be attributed to the shorter time for carbohydrate and nutrient relocation and as the leaves - which contain most nutrients - are also harvested [47]. The higher nutrient offtake of green biomass needs to be considered in the fertilization management. To ensure enough time for the rhizomes to refill their carbohydrate stocks, several studies recommend a green harvest in October for biogas utilisation, as this harvest time enables high methane yields, a sufficient silage quality to store the biomass and a sufficient green-cut tolerance [32,33,47].

The management steps shown are based on the recent scientific literature and thus also include some which are currently not applied in practical miscanthus farming. However, those steps, for example the application of the mulch film, were intentionally included to cover all possible costs, which can be incurred (Section 3.3). If a miscanthus grower chooses not to apply individual steps, the respective costs (shown in Table 2) can be omitted. Additionally, in this study removed nutrients are replaced by digestate application in the conventional and organic biogas pathways, but by mineral fertilizers in the animal bedding and combustion pathways. This is to exemplify the costs of different fertilisation regimes and are interchangeable between the different utilisation pathways.

3.2. Lands potentially suitable for miscanthus cultivation

The following section gives an overview of the beneficial characteristics of miscanthus cultivation, providing evidence of the crop's high suitability to be grown on marginal land [71–73].

3.2.1. Soil erosion prevention

Miscanthus stands cover the soil over a long period of time - if harvested after winter, almost the complete year. The soil structure can also improve since, after successful establishment, the soil is no longer tilled. Permanent soil cover reduces soil erosion and nutrient leaching, which leads to a substantial reduction in nutrients draining into rivers and water bodies [2,4,74], thus protecting aquatic ecosystems from alteration through eutrophication. Sole cultivation of perennial grasses on arable slopes can prevent water erosion completely [75]. In strip cultivation with annual crops, such as cereals and energy crops, water erosion (up to a gradient of 14°) can be reduced by up to 80% [74,75]. Hence, perennial crop cultivation protects soil resources [4], especially where they are susceptible to erosion.

3.2.2. Carbon storage and soil fertility improvement

The carbon storage potential of miscanthus is considerable, due to its long cultivation period. Its annual C storage potential can be as high as 2.2 t C_4-C ha^{-1} a^{-1} [2]. This is in the same order of magnitude as for perennial grassland [76]. Felten and Emmerling (2012) [77] measured a carbon storage of 17.7 t C ha^{-1} in the top 60 cm of soil over a 16-year miscanthus cultivation period in Germany. Clifton-Brown et al. (2007) [78] found a lower carbon sequestration of 8.9 t C ha^{-1} over a 15-year cultivation period in Ireland and reported that the increase in soil organic carbon originates from dead belowground biomass (about 25% of rhizomes and roots die annually) and annual leaf fall [78].

Soil organic carbon is an important indicator of soil biota, as it provides a food and energy source for microorganisms [79]. Furthermore, soil organic carbon improves the soil structure through higher aggregate stability, which in turn improves water infiltration potential, soil water-holding capacity and aeration, and also reduces soil erosion [80]. Additionally, humus is an important source of plant nutrients with a high cation exchange capacity, thus improving nutrient availability for the plants [79].

As such, miscanthus cultivation over a 20-year period can significantly increase soil fertility, helping improve both depleted and marginal soils [81].

3.2.3. Cultivation of miscanthus on marginal lands

The scenarios assessed in Sections 3.2 and 3.3 consider miscanthus cultivation on both good and marginal site conditions. In this study, 'good' and 'marginal' refer to the overall economic relevance of a site, which is a product of abiotic and biotic factors [82–85]. In the cost (Section 3.2) and labour (Section 3.3) assessment, it was assumed that field size plays an important role in the economic relevance of cultivation management and logistics. For this reason, the assessments included cultivation on 1 ha and farm-field distance of 10 km to cover the scenarios of fields far away from the farm as well as cultivation on multiple small patches with to a total area of 1ha and a considerable driving distance between them.

Miscanthus cultivation on relatively small and irregularly shaped fields could be an interesting alternative to annual crops, because of the low tillage demand (once in a 20-year plantation lifetime). An annual crop cultivation is hardly economically feasible here due to the heavy tillage workload (Section 3.3) and difficulties with large machinery unsuitable for small and irregular shaped fields [12]. Consequently, miscanthus cultivation can be economically beneficial on awkward and scattered fields as well as on buffer strips e.g. next to rivers, water bodies or groundwater protection areas.

Another benefit associated with low tillage requirements is the cultivation of miscanthus on soils with a high clay content that can only be accessed by machinery for a short time period [86]. According to the 'World Reference Soil Base', soils with *clayic* properties, such as Vertisols or Luvisols [87], fall into this category. C*layic* soils become greasy when moist, and hard when dry. Hence, tillage with heavy machinery is only possible in an often very short time span when the soils are neither too moist nor too dry. *Clayic* soils are typically used for permanent grassland, orchards and forests [88].

Miscanthus cultivation may be a feasible new option on *clayic* soils. However farmers need to carefully assess other soil properties as some, such as Stagnosols and Gleysols [87], can be permanently or periodically waterlogged and are therefore deemed unsuitable [36]. On the other hand, a study by Mann et al. (2013) [89] showed that miscanthus is able to tolerate natural flooded conditions and thus high soil moisture contents.

Miscanthus forms dense stands from year three onwards, which can possibly suppress resistant weeds naturally [90]. For this reason, Clifton-Brown et al. (2017) [12] proposed cultivating miscanthus on fields with high weed pressure, particularly with herbicide-resistant weeds, as an ecologically sound melioration measure.

3.2.4. EU CAP ecological focus area: greening

The perennial crop miscanthus provides a wide range of ecosystem functions such as biodiversity conservation [76,91–94], soil organic carbon accumulation [76,95], soil structure improvement and erosion protection [2] as well as the reduction of greenhouse gas emissions [76]. Due to these advantages, Emmerling and Pude (2017) [76] recommended miscanthus as an additional crop for the 'Ecological Focus Areas' of the EU Common Agricultural Policy (CAP). In 2018, article 45 of the Delegated Regulation (EU) No 639/2014 was amended by paragraph 8a, which states that the perennial crops miscanthus and cup plant (*Silphium perfoliatum* L.) are allowed to be cultivated on ecological focus areas, but on the condition that plant protection measures are only applied in the year of establishment [52]. On 15.02.2019, the German Federal Council banned the application of mineral fertilizers completely on ecological focus areas in Germany [96]. This makes miscanthus, which can also be cultivated without nitrogen fertilization, very suitable for such areas [97].

3.2.5. Riversides and groundwater protection areas

Miscanthus can also be grown as buffer strips alongside waterbodies, reducing soil erosion and nutrient run-off and thus promoting water protection [97]. The application of chemical plant protection and mineral fertilizer is prohibited in a 5m-wide buffer strip alongside waterbodies. This may negatively affect the yield of annual crops and could be an advantage for miscanthus, since it can be grown without chemical crop protection and fertilization and would allow farmers to use these areas productively without negative impacts on water quality.

Table 2

Overview of miscanthus production costs for the utilisation pathways combustion, animal bedding, biogas and organic biogas for two yield levels and two field sizes (farm-field distance = 10 km).

	1 ha								10 ha							
	Combustion		Animal bedding		Biogas		Organic biogas		Combustion		Animal bedding		Biogas		Organic biogas	
Harvest date	March		March		October		October		March		March		October		October	
Harvest process	Chopper		Chopper + baler		Chopper		Chopper		Chopper		Chopper + baler		Chopper		Chopper	
Yield level [t DM ha^{-1} a^{-1}]	15	25	15	25	15	25	15	25	15	25	15	25	15	25	15	25
Establishment (1st year) [€ ha^{-1} a^{-1}]	**3743**		**3743**		**3743**		**3317**		**3632**		**3632**		**3632**		**3182**	
- Machine costs	408		408		408		475		356		356		356		413	
- Material costs	2931		2931		2931		2408		2931		2931		2931		2408	
- Energy costs	120		120		120		142		106		106		106		127	
- Labour costs	245		245		245		249		205		205		205		197	
- Interest rate	38		38		38		43		34		34		34		38	
Harvest phase (2nd - 19th year) [€ ha^{-1} a^{-1}]	**471**	**624**	**708**	**1022**	**582**	**807**	**582**	**794**	**413**	**569**	**633**	**950**	**514**	**741**	**514**	**741**
- Machine costs	244	291	414	575	370	498	370	498	199	248	361	522	320	452	320	452
- Material costs	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
- Fertilizer costs	104	173	104	173	0	0	0	0	104	173	104	173	0	0	0	0
- Energy costs	50	69	51	72	95	141	95	141	45	65	44	65	90	140	90	140
- Labour costs	37	51	88	137	69	107	69	107	35	49	81	130	62	94	62	94
- Interest rate	28	32	43	58	41	54	41	41	22	27	37	51	35	48	35	48
Harvest & removal (20th year) [€ ha^{-1} a^{-1}]	**488**	**566**	**725**	**964**	**635**	**812**	**635**	**812**	**405**	**486**	**625**	**866**	**540**	**719**	**540**	**719**
- Machine costs	317	361	487	644	400	498	400	498	257	303	419	577	335	436	335	436
- Material costs	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
- Energy costs	78	96	78	99	110	148	110	148	69	89	69	90	102	144	102	144
- Labour costs	51	63	102	149	75	106	75	106	43	55	89	136	61	85	61	85
- Interest rate	34	38	50	64	43	54	43	54	27	31	42	56	35	46	35	46
Annual Ø-production costs [€ ha^{-1}]	**635**	**777**	**860**	**1155**	**743**	**954**	**721**	**933**	**574**	**718**	**783**	**1080**	**671**	**884**	**648**	**862**
Biomass production costs [€ t^{-1} a^{-1}]	**47**	**35**	**64**	**51**	**55**	**42**	**53**	**41**	**42**	**32**	**58**	**48**	**50**	**39**	**48**	**38**
Methane costs [€ m^{-3}]					**0.23**	**0.18**	**0.23**	**0.18**					**0.21**	**0.17**	**0.20**	**0.16**
Min/max selling price [€/t^{-1}]	65–95		106–600		1373 (field)/118 (chopped)				65–95		106–600		1373 (field)/118 (chopped)			
Min/max sales revenue [€ ha^{-1} a^{-1}]	**975–1425**	**1625–2375**	**1590–9000**	**2650–15,000**	**1373** (field) – **2950** (chopped)				**975–1425**	**1625–2375**	**1590–9000**	**2650–15,000**	**1373** (field) – **2950** (chopped)			
Attainable gross margin [€ ha^{-1} a^{-1}]	**340–790**	**848–1598**	**730–8140**	**1495–13,845**	**1027–1996** (chopped) **1222–1266** (field)		**1049–2017** (chopped) **1230–1244** (field)		**401–851**	**907–1657**	**807–8217**	**1570–13,920**	**1099–2066** (chopped) **1204–1218** (field)		**1122–2088** (chopped) **1383–1387** (field)	

3.3. Biomass production cost assessment

The cultivation cost assessments for miscanthus used for combustion, animal bedding and biogas are summarized in Table 2. The highest costs are incurred for crop establishment in the first year. The rhizomes account for the largest share of costs, at a selling price 0.16 € each [98]. The total rhizome costs amount to 2400 € for an average planting density of 15,000 rhizomes ha^{-1} including re-planting [13,36,38,39]. If miscanthus cultivation is extended in future, it can be expected that the harvest costs of currently about 0.052 € per rhizome [99] will decrease and thus also lead to a reduction in rhizome selling prices.

A biodegradable mulch film can help reduce planting density and thus rhizome costs, but is at the same time another cost driver during establishment (280 € ha^{-1} [42]). Mulch film application is recommended as it accelerates plant establishment and early growth rates (number of shoots), thus reducing the time until the first mature miscanthus harvest [42]. In addition, Olave et al. (2017) reported a yield increase of up to 30% [42,43]. The costs for the mulch film could be offset by a reduction of 1800 rhizomes per hectare, achievable through improved establishment. However, the reported benefits of a mulch film are specific to the site and miscanthus variety [42,43]. In this study, application of mulch film was integrated in the biomass production cost assessment. If farmers decide to omit it, the costs (347.70 € ha^{-1} in 1-ha scenario, 344.24 € ha^{-1} in 10-ha scenario) can easily be subtracted from the establishment costs given in Table 2.

Another important cost driver is the field-to-farm distance, because large biomass quantities need to be transported, especially when miscanthus is harvested 'green' in October. For this harvest date, fresh matter weight has been determined as 43 to 71 t ha^{-1} with a relatively low dry matter content of 35% [33]. The low density of chopped miscanthus (75 kg m^{-3}) is problematic [100], as the large volume quickly fills the trailers used for transport. The reference trailer used here has a volume of 50 m^3 and maximum load of 10 t, but can only accommodate 3.75 t of chopped miscanthus biomass. Compaction of the chaff through baling increases the density to up to 200 kg m^{-3}, making field-farm transport much more efficient. However, baling requires additional machinery with respective costs for maintenance and depreciation as well as additional labour input (Table 2).

The fertilizer costs for a nutrient removal-based management are 104 € ha^{-1} for the medium-yield scenario and 173 € ha^{-1} for the high-yield scenario, including machine costs of 6–9 € ha^{-1} a^{-1} and labour costs of 4–6 € ha^{-1} a^{-1}. For the utilisation pathways 'biogas' and 'organic biogas' (Table 1), fertilising with digestates avoids the costs for the external inputs, but increases machine and labour costs substantially. In the high-yield scenario of the utilisation pathways 'biogas' and 'organic biogas', digestate application accounts for machine costs of about 80 € ha^{-1} and labour costs of about 20 € ha^{-1} (2.1 h ha^{-1}). In the medium-yield scenario, about 50 € ha^{-1} machine costs and about 12 € ha^{-1} labour costs are incurred. Consequently, the total costs of mineral fertilisation are about 114 € ha^{-1} a^{-1} (medium-yield level) to 188 € ha^{-1} a^{-1} (high-yield level), while the total costs for fertilisation with digestate are about 62 € ha^{-1} a^{-1} (medium yield) to 100 € ha^{-1} a^{-1} (high yield).

Labour requirements for the establishment phase are high, with costs ranging between 197 € ha^{-1} and 249 € ha^{-1} for the utilisation pathways assessed here. In the harvest years, the labour costs are comparably low for the combustion pathway (35–51 € ha^{-1}), followed by both biogas pathways (62–107 € ha^{-1}), and highest for the animal bedding pathway (81–137 € ha^{-1}) due to the additional step of bale pressing and loading in the harvest procedure.

3.3.1. Combustion

Miscanthus cultivation for combustion has the lowest biomass production costs. Here it is harvested in March using a row-independent chopper. The high dry matter content (typically more than 80% [33], allows for direct storage and combustion. In the 1-ha cultivation area scenario, the biomass can be produced for 47 € t^{-1} at the medium-yield level and for 35 € t^{-1} at the high-yield level. Increasing the cultivation area to 10 ha further reduces the biomass production costs to 42 € t^{-1} (medium yield) and 32 € t^{-1} (high yield). Current selling prices for chopped miscanthus biomass for combustion vary considerably across Europe and the US (48–134 € t^{-1}) [15]. Taking a medium price range of 65 € t^{-1} [40] to 95 € t^{-1} [101], the attainable gross margins range from 401 € ha^{-1} to 1657 € ha^{-1} in the 10-ha scenario and from 340 € ha^{-1} to 1598 € ha^{-1} in the 1-ha scenario (Table 2).

3.3.2. Animal bedding

Miscanthus used for animal bedding is also harvested in March [57]. In contrast to the combustion utilisation pathway, here the biomass is chopped into 20–30 cm pieces, laid in a swath and picked up by a bale press. The bales are subsequently transported to the farm. This pathway has the highest production costs of all investigated utilisation options: 860 € ha^{-1} (medium yield) to 1155 € ha^{-1} (high yield) for the 1-ha cultivation area scenario, and slightly lower at 783 € ha^{-1} (medium yield) to 1080 € ha^{-1} (high yield) for the 10-ha cultivation area.

However, this utilisation option is very lucrative due to the evolving market for miscanthus straw as animal bedding material. Miscanthus is currently receiving growing attention in the horse sector in particular [102,103], but it is also a viable alternative bedding material for dairy cows [46]. Additionally, the very dry growing season in 2018 led to a greatly increased price of 106 ± 21 € t^{-1} for straw in Germany [96], rendering miscanthus a promising alternative.

The calculations give an attainable gross margin of 807 € ha^{-1} (medium-yield level) to 1570 € ha^{-1} (high-yield level) for baled miscanthus straw, based on the reference price of wheat straw of 106 ± 21 € t^{-1} in December 2018 [104]. The attainable gross margin becomes even higher (8217 € ha^{-1} for medium yield to 13,920 € ha^{-1} for high yield) if current market prices of up to 600 € t^{-1} for dedusted bedding material are considered [105], e.g. for small domestic animals and sport horses. Note that dust removal, which is comparatively expensive, and transport to end-customer are not included in the calculation.

3.3.3. Conventional biogas production

Recent research has revealed that miscanthus is also a suitable feedstock for anaerobic digestion [32,47]. Even though specific methane yields are lower for miscanthus than for maize [62], miscanthus can achieve methane hectare yields of 5000 to 6000 m^3 CH_4 ha^{-1} (comparable to those of maize) due to its high biomass yields [32–34]. To attain these high methane hectare yields, the miscanthus biomass has to be harvested when the contents of easily digestible biochemical components, such as hemicellulose and water-soluble sugars, are high and lignin contents are low [33,47,106]. The optimal harvest date has been determined as (mid-)October [33,47].

In the scenario of miscanthus cultivation for biogas production, mineral fertilisation during the productive phase was entirely replaced by application of the biogas digestate. The annual (NPK) application rates based on nutrient removal were determined as 15.4 t FM ha^{-1} unseparated digestate for the medium-yield scenario and 25.7 t FM ha^{-1} for the high-yield scenario [33,44,45,47,107]. The crop requires higher nutrient application rates in the green than the brown harvest regime, as nutrient relocation to the rhizomes and leaf fall has not taken place (Table 1).

The annual production costs of miscanthus for anaerobic digestion are between those of the other utilisation options investigated and range from 743 € ha^{-1} (medium-yield level) to 954 € ha^{-1} (high-yield level) for the 1-ha scenario. This corresponds to biomass production costs of 42 € t^{-1} (high yield) to 55 € t^{-1} (medium yield). For the 10-ha scenario, the annual production costs are between 671 € ha^{-1} (medium-yield level) and 884 € ha^{-1} (high-yield level) with biomass production costs between 39 € t^{-1} (high yield) and 50 € t^{-1} (medium yield). Methane production costs range from 0.23 € $(m^3\ CH_4)^{-1}$ (medium yield) to 0.18 € $(m^3\ CH_4)^{-1}$ (high yield) in the 1-ha scenario, and from 0.17 € $(m^3\ CH_4)^{-1}$ (medium yield) to 0.21 $(m^3\ CH_4)^{-1}$ (high yield) in the 10-ha scenario. These are comparable to or even lower than the methane production costs of maize, specified by FNR 2019 [22] as 0.19 to 0.29 € (m^3 CH_4)$^{-1}$ and by the North Rhine-Westphalian Chamber of Agriculture [108] as 0.28 to 0.34 € (m^3 CH_4)$^{-1}$. Consequently, miscanthus is an economically viable biogas crop that can be considered an alternative to maize.

Two scenarios were analysed:

i) Miscanthus is sold as standing crop to the biogas plant owner who organizes and pays for the harvest. In Germany, maize is often sold in this way at an average price of 1373 € ha^{-1} [109]. However, this value cannot be transferred directly to miscanthus, as miscanthus needs to be pre-treated to achieve a comparable substrate-specific methane yield to maize [47,110]. To finance such a pre-treatment plant, the biogas plant operator needs additional capital for the plant and its operation. To take this into account, a deduction of 10% on the average price of maize was applied in this study (Table 2).This results in an attainable gross margin for miscanthus of 1204 to 1218 € ha^{-1} in the 10-ha scenario and 1222 to 1266 € ha^{-1} in the 1-ha scenario. The reason for this only very slightly higher margin in the 10-ha scenario is that the biogas plant owner (not the miscanthus grower) directly covers the costs of digestate application and harvesting (both drivers of production costs).

ii) Harvested miscanthus is sold to the biogas plant owner as feedstock or used in the farm's own biogas plant. In this scenario, the attainable gross margin is 1027 to 1996 € ha^{-1} in the 1-ha scenario and 1099 to 2066 € ha^{-1} in the 10-ha scenario (average price 2950 € ha^{-1}). Here it is assumed that all costs for crop production are covered by the farmer, including digestate application and harvest by field chopper.

3.3.4. *Organic biogas production*

The organic production of biogas was investigated as this production system is in accordance with the EU's recently revised 'greening' regulations and is also deemed suitable for riparian buffer strips. In contrast to conventional biogas production, the organic cultivation system relies on fertilisation with digestate (for application rates, see 4.2.3) and mechanical weeding before establishment (harrowing twice) and after establishment (hoeing 4 times). Application of a mulch film is thus not applicable here.

Establishment costs (10 ha: 3182 € ha^{-1}; 1 ha: 3317 € ha^{-1}) are lower than in the conventional system (10 ha: 3632 € ha^{-1}; 1 ha: 3743 € ha^{-1}). Less materials (mulch film) and inputs (fertilizer and pesticides) need to be purchased. Labour costs are very similar to the conventional system, but energy and machine costs are higher, mainly due to the mechanical weeding (Table 2).

The overall annual production costs for organic biogas production are slightly lower than in the conventional system: 721 € ha^{-1} (medium-yield level) to 933 € ha^{-1} (high-yield level) with biomass production costs of 41 € t^{-1} (high yield) to 53 € t^{-1} (medium yield) for the 1-ha scenario and 648 € ha^{-1} (medium-yield level) to 862 € ha^{-1} (high-yield level) with biomass production costs of 38 € t^{-1} (high yield) to 48 € t^{-1} (medium yield) for the 10-ha scenario. Consequently, the methane production costs are also similar to those of conventional miscanthus feedstock production: 0.18 € (m^3 CH_4)$^{-1}$ (high yield) to 0.23 € (m^3 CH_4)$^{-1}$ (medium yield) in the 1-ha scenario and 0.17 € (m^3 CH_4)$^{-1}$ (medium yield) to 0.21 (m^3 CH_4)$^{-1}$ (high yield) in the 10-ha scenario.

The attainable gross margins in scenario *i)* are 1378 to 1392 € ha^{-1} in the 1-ha and 1383 to 1387 € ha^{-1} in the 10-ha scenario. In scenario *ii)*, they are 1049 to 2017 € ha^{-1} (1-ha) and 1122 to 2088 € ha^{-1} (10-ha scenario) (Table 2).

3.3.5. *Accumulated production costs*

The total production costs for the four utilisation pathways investigated vary considerably (Fig. 3). Combustion has the lowest aggregated production costs at 14,356 € ha^{-1} on 10 ha and 15,537 € ha^{-1} on 1 ha over a 20-year cultivation phase. Miscanthus chaff can either be self-utilized for decentral energy generation on farm or sold at 65 to 95 € t^{-1} [40,101]. Hence, a potential overall sales revenue of 17,550 € ha^{-1} (medium yield; 65 € t^{-1}) to 42,750 € ha^{-1} (high yield; 95 € t^{-1}) can be achieved.

For anaerobic digestion, the overall aggregated production costs are 19,085 € ha^{-1} (18,659 € ha^{-1} for organic biogas) when cultivating on 1 ha and 17,687 € ha^{-1} (17,237 € ha^{-1} for organic biogas) on 10 ha. Methane yields comparable to maize can be achieved, thus selling miscanthus at a price of 118 € t^{-1} (average selling price on ebay.de, at the harvest time of silage maize in 2018) results in potential sales revenues of 31,860 € ha^{-1} (medium-yield level) to 53,100 € ha^{-1} (high-yield level).

Due to the fact that for animal bedding the chopped miscanthus material is baled, this pathway has the highest aggregated production

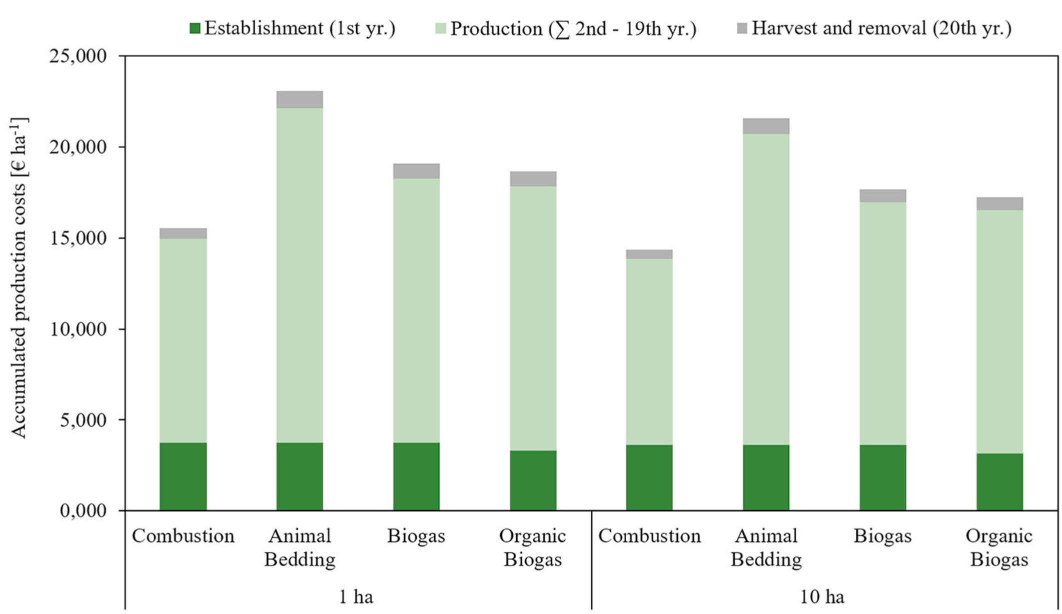

Fig. 3. Overview of calculated production costs for the years of establishment (1st year), production (2nd-19th year) and removal (20th year) under different growing conditions (land size) and utilisation pathways (harvest date varies) for the high yield level (25 t DM ha^{-1}).

costs at 21,593 € ha^{-1} on a 10-ha and 23,102 € ha^{-1} on a 1-ha cultivation area (Fig. 3). Taking the current straw price in Germany as reference (106 € t^{-1} [104], the sales revenues for miscanthus as a straw alternative vary from 28,620 € ha^{-1} (medium-yield level) to 47,700 € ha^{-1} (high-yield level), end-customer transport and dedusting excluded. Harvest and removal costs in year 20 vary between the utilisation pathways due to the different harvest procedures.

In summary: The lowest biomass production costs are incurred for miscanthus harvested brown with a chopper, followed by a green harvest for anaerobic digestion. The highest production costs are incurred for a brown harvest using chopper and baler.

The biomass selling prices vary considerably between utilisation pathways and ultimately determine the attainable gross margins to a large extent. The potentially attainable gross margins are in the order: combustion < biogas < organic biogas < animal bedding. In this context, it should be mentioned that the same yield level was assumed for the organic biogas pathway as for the conventional pathway. However, as mechanical weeding is conducted in the organic pathway, the yield may possibly be lower [90], thus reducing sales revenue, at least in the establishment years, due to a higher weed pressure. Moreover, this study assumed that mechanical weeding has to be conducted four times [48]. As no literature was available for the organic cultivation of miscanthus, it is possible that more mechanical weeding is necessary for an efficient weed management, again reducing sales revenues.

In addition, as no other prices were found for miscanthus sold for anaerobic digestion, it was assumed that miscanthus can be sold for 90% of the price of maize (due to the aforementioned need for pre-treatment of miscanthus). Recent studies [32,34,47,62] found similar methane hectare yields for miscanthus and maize under experimental conditions. This finding, however, needs to be verified in practice, as the price parity assumption may be rather optimistic. As a biogas substrate, miscanthus is currently likely to be sold at a lower price than maize, on account of the (currently) lower biogas quality which requires pre-treatment [47]. However, if miscanthus breeding improves novel genotypes, for example through better digestibility or higher methane hectare yields, similar selling prices as for maize could probably be achieved.

3.4. Labour requirements of miscanthus cultivation

When considering the introduction of a new crop into an existing crop rotation, the crop's economic performance is of primary importance to a farmer. In addition, labour requirements and their distribution throughout the year are of particular importance.

Tables 3 a,b provide a detailed overview of labour requirements and distribution for the four miscanthus utilisation pathways investigated. It can be seen that cultivation on 1 ha (Table 3a) has a lower labour efficiency than on 10 ha (Table 3b). This can mainly be attributed to the preparation time for each working step.

The total labour input over the 20-year cultivation period is lowest for the combustion pathway, followed by biogas, and highest for the animal bedding pathway (Table 3 a,b).

Labour input is highest in the year of establishment, in particular in April when the rhizomes are planted. Here, the organic biogas pathway has slightly higher time requirements in the 1-ha scenario, while in the 10-ha scenario the organic establishment method shows lower labour input due to the allocation of the preparation time to a larger land size.

Once the miscanthus stand is established, the labour requirement in the 18 harvest years range from 4.0 to 14.8 h ha^{-1} (1-ha scenario) and 3.8–14.1 h ha^{-1} (10-ha scenario). The large variations can be attributed to the different harvest methods and dates. While a chopper harvesting of 1 ha miscanthus in March requires 2.6–3.9 h ha^{-1} (15 and 25 t DM ha^{-1}), the additional baling increases the harvest time to 7.3–12.2 h ha^{-1} (15 and 25 t DM ha^{-1}). A green harvest in October approximately doubles the labour requirements (5.0–8.3 h ha^{-1}, for 15 and 25 t DM ha^{-1}) compared to a chopper harvest in March, due to the considerably higher fresh matter weights.

The removal year has slightly higher labour efforts than the harvest years. This can be attributed to the ploughing of the fields after the final harvest.

In the following sections, the labour requirements for miscanthus cultivation are compared to both an annual crop rotation and to other perennial crops as a form of reference and decision support for farmers.

3.4.1. Labour requirement comparison miscanthus - annual crop rotation

The comparison of miscanthus (green and brown harvest) with a conventional annual crop rotation based on maize, other cereal crops and intermediate crops shows that miscanthus cultivation offers the potential of staggering a farm's labour peaks (Fig. 4).

Once the miscanthus stand is established, fertilization takes place in early spring in both the brown and green harvest regime. The work distribution in the green harvest regime for biogas matches that for silage maize, but the labour peaks do not coincide with those of the other cereals or intermediate crops. By contrast, the brown harvest regime has labour requirements that coincide with those for some of the other crops e.g. for soil preparation (spring barley, maize, phacelia), fertilization (winter barley, maize) and removal/harvest (phacelia, mustard). However, there is only one labour peak in March, with no other labour-intensive periods during the rest of the year. Hence, a brown-harvest regime also provides some relief in a farm's labour peak seasons.

3.4.2. Labour requirement comparison miscanthus – other perennial crops

The comparison of the labour distribution of miscanthus cultivation with that of the reference crop poplar (in the form of perennial short rotation coppice) revealed that the two have very similar cropping patterns (Fig. 5a). The only difference detected was in the harvest time. Whereas poplar is harvested in December every 3–5 years [111], miscanthus is harvested every year, either brown in March or from the second year onwards green in October [49,112].

Hence, the miscanthus green harvest regime has a labour peak in October from year 2 to year 20. A similar labour distribution pattern is seen for cup plant (Fig. 5b), an alternative perennial biogas crop that was also approved for greening measures in 2018 [52]. In cup plant cultivation, soil preparation, fertilization with digestate and sowing is performed in April, and a chopper-based harvest in late September. From the second year onwards, cup plant is fertilized with digestate annually at the beginning of the growing season in April. As cup plant is established by seed (and not rhizome planting as in miscanthus), the labour peak in spring is much lower. However, the labour peak of the cup plant harvest is higher than for miscanthus. This is because cup plant is harvested with a higher water content.

Hence, the labour peaks for miscanthus are higher for establishment, but afterwards lower than those of the alternative crops for the same utilisation. For brown-harvested miscanthus, the peaks fall prior to the preparation and sowing season of annual crops. Therefore, miscanthus cultivation can potentially benefit a farm's labour distribution.

4. Conclusions

The implementation of miscanthus into farming systems can be lucrative in the following cases: 1) for fields or lands with unfavourable conditions, such as awkward shapes, slopes or low soil quality; 2) for greening areas or areas need for ecological services, such as soil protection, 3) when the farmer can either use the biomass on his own farm or sell it at a reasonable price. In the last case, lucrative utilisation pathways include combustion, animal bedding and anaerobic digestion.

From an economic point of view, animal bedding was found to be the most profitable utilisation pathway, mainly due to the high selling prices. These can best be achieved when small quantities are sold e.g. to hobby animal keepers or sport horse stud farms, in particular for dedusted miscanthus chips. Miscanthus bedding provides the animals with better hygienic standards and comfort than straw. As such, it also provides farms with animal husbandry a promising on-farm use

Table 3a
Overview of labour requirements and its annual distribution in miscanthus production for the utilisation pathways combustion, animal bedding, conventional biogas and organic biogas for two yield levels on a **1-ha** field.

	Combustion				Animal bedding				Biogas				Organic biogas			
Harvest date	March				March				October				October			
Harvest process	Chopping				Chopping + baling				Chopping				Chopping			
Yield level [t DM ha-1]			15	25			15	25			15	25			15	25
Establishment (1st year) [h ha-1]	**Type of work**	**Month**	**34.92**		**Type of work**	**Month**	**34.92**		**Type of work**	**Month**	**34.92**		**Type of work**	**Month**	**35.31**	
	Ploughing	October	1.97		Ploughing	October	1.97		Ploughing	October	1.97		Ploughing	October	1.97	
	Rotary harrowing	April	1.29		Rotary harrowing	April	1.29		Rotary harrowing	April	1.29		Rotary harrowing	April	1.29	
	Chemical weeding	April	0.23		Chemical weeding	April	0.23		Chemical weeding	April	0.23		Rotary harrowing	April	1.29	
	Rhizome transport	April	1.39		Rhizome transport	April	1.39		Rhizome transport	April	1.39		Rhizome transport	April	1.39	
	Rhizome planting	April	23.48		Rhizome planting	April	23.48		Rhizome planting	April	23.48		Rhizome planting	April	23.48	
	Irrigation	April	1.21		Irrigation	April	1.21		Irrigation	April	1.21		Irrigation	April	1.21	
	Plastic cover	April	3.68		Plastic cover	April	3.68		Plastic cover	April	3.68		Mechanical weeding	May	0.81	
	Chemical weeding	April	0.23		Chemical weeding	April	0.23		Chemical weeding	April	0.23		Mechanical weeding	May	0.81	
	Mulching	March	1.44		Mulching	March	1.44		Mulching	March	1.44		Mechanical weeding	June	0.81	
													Mechanical weeding	June	**0.81**	
													Mulching	October	1.44	
Harvest phase (2nd - 19th year) [h ha-1]	**Type of work**	**Month**	**4.02**	**5.54**	**Type of work**	**Month**	**9.54**	**14.81**	**Type of work**	**Month**	**7.46**	**11.60**	**Type of work**	**Month**	**7.46**	**11.60**
	Soil sampling	February	0.29	0.29	Soil sampling	February	0.29	0.29	Soil sampling	November	0.29	0.29	Soil sampling	November	0.29	0.29
	Chopping	March	0.66	0.66	Chopping	March	0.66	0.66	Chopping	October	0.84	0.84	Chopping	October	0.84	0.84
					Baling	March	0.83	1.02								
	Transport to farm	March	2.62	3.94	Transport to farm	March	7.31	12.19	Transport to farm	October	4.99	8.34	Transport to farm	October	4.99	8.34
	Fertilizer application	April	0.45	0.65	Fertilizer application	April	0.45	0.65	Fertilizer application	November	1.34	2.13	Fertilizer application	November	1.34	2.13
Harvest & removal (20th year) [h ha-1]	**Type of work**	**Month**	**5.54**	**6.86**	**Type of work**	**Month**	**11.06**	**16.13**	**Type of work**	**Month**	**8.09**	**11.44**	**Type of work**	**Month**	**8.09**	**11.44**
	Soil sampling	February	0.29	0.29	Soil sampling	February	0.29	0.29	Soil sampling	November	0.29	0.29	Soil sampling	November	0.29	0.29
	Chopping	March	0.66	0.66	Chopping	March	0.66	0.66	Chopping	October	0.84	0.84	Chopping	October	0.84	0.84
					Baling	March	0.83	1.02								
	Transport to farm	March	2.62	3.94	Transport to farm	March	7.31	12.19	Transport to farm	October	4.99	8.34	Transport to farm	October	4.99	8.34
	Ploughing	March	1.97	1.97	Ploughing	March	1.97	1.97	Ploughing	November	1.97	1.97	Ploughing	November	1.97	1.97
Total labour effort [h ha-1]			**112.82**	**141.50**			**217.70**	**317.63**			**177.29**	**255.16**			**177.68**	**255.55**

Table 3b
Overview of labour requirements and its annual distribution in miscanthus production for the utilisation pathways combustion, animal bedding, conventional biogas and organic biogas for two yield levels on a **10-ha** field.

	Combustion				Animal bedding				Biogas				Organic biogas			
Harvest date	March				March				October				October			
Harvest process	Chopping				Chopping + baling				Chopping				Chopping			
Yield level [t DM ha-1]			15	25			15	25			15	25			15	25
Establishment (1st year) [h ha-1]	**Type of work**	**Month**	**29.67**		**Type of work**	**Month**	**29.67**		**Type of work**	**Month**	**29.67**		**Type of work**	**Month**	**29.09**	
	Ploughing	October	1.28		Ploughing	October	1.28		Ploughing	October	1.28		Ploughing	October	1.28	
	Rotary harrowing	April	0.88		Rotary harrowing	April	0.88		Rotary harrowing	April	0.88		Rotary harrowing	April	0.88	
	Chemical weeding	April	0.13		Chemical weeding	April	0.13		Chemical weeding	April	0.13		Rotary harrowing	April	0.88	
	Rhizome transport	April	0.69		Rhizome transport	April	0.69		Rhizome transport	April	0.69		Rhizome transport	April	0.69	
	Rhizome planting	April	20.84		Rhizome planting	April	20.84		Rhizome planting	April	20.84		Rhizome planting	April	20.84	
	Irrigation	April	1.25		Irrigation	April	1.25		Irrigation	April	1.25		Irrigation	April	1.25	
	Plastic cover	April	3.32		Plastic cover	April	3.32		Plastic cover	April	3.32		Mechanical weeding	May	0.53	
	Chemical weeding	April	0.13		Chemical weeding	April	0.13		Chemical weeding	April	0.13		Mechanical weeding	May	0.53	
	Mulching	March	1.15		Mulching	March	1.15		Mulching	March	1.15		Mechanical weeding	June	0.53	
													Mechanical weeding	June	**0.53**	
													Mulching	October	1,15	
Harvest phase (2nd - 19th year) [h ha-1]	**Type of work**	**Month**	**3.83**	**5.31**	**Type of work**	**Month**	**8.72**	**14.07**	**Type of work**	**Month**	**6.65**	**10.11**	**Type of work**	**Month**	**6.65**	**10.11**
	Soil sampling	November	0.14	0.14	Soil sampling	February	0.14	0.14	Soil sampling	November	0.14	0.14	Soil sampling	November	0.14	0.14
	Chopping	March	0.41	0.42	Chopping	March	0.41	0.41	Chopping	October	0.52	0.53	Chopping	October	0.52	0.53
					Baling	March	0.36	0.56								
	Transport to farm	March	2.87	4.12	Transport to farm	March	7.4	12.33	Transport to farm	October	4.64	7.26	Transport to farm	October	4.64	7.26
	Fertilizer application	April	0.41	0.63	Fertilizer application	April	0.41	0.63	Fertilizer application	November	1.35	2.18	Fertilizer application	November	1.35	2.18
Harvest & removal (20th year) [h ha-1]	**Type of work**	**Month**	**4.70**	**5.96**	**Type of work**	**Month**	**9.59**	**14.72**	**Type of work**	**Month**	**6.58**	**9.21**	**Type of work**	**Month**	**6.58**	**9.21**
	Soil sampling	February	0.14	0.14	Soil sampling	February	0.14	0.14	Soil sampling	November	0.14	0.14	Soil sampling	November	0.14	0.14
	Chopping	March	0.41	0.42	Chopping	March	0.41	0.41	Chopping	October	0.52	0.53	Chopping	October	0.52	0.53
					Baling	March	0.36	0.56								
	Transport to farm	March	2.87	4.12	Transport to farm	March	7.4	12.33	Transport to farm	October	4.64	7.26	Transport to farm	October	4.64	7.26
	Ploughing	March	1.28	1.28	Ploughing	March	1.28	1.28	Ploughing	November	1.28	1.28	Ploughing	November	1.28	1.28
Total labour effort [h ha-1]			**103.31**	**131.21**			**196.22**	**297.65**			**155.95**	**220.86**			**155.37**	**220.28**

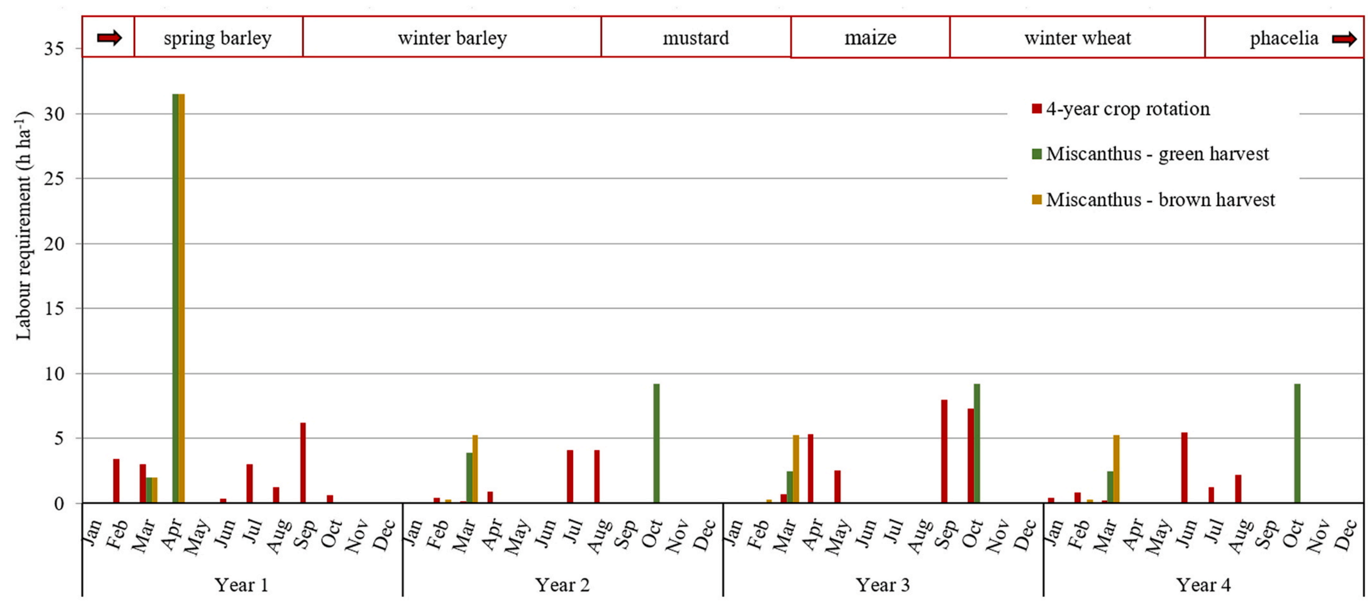

Fig. 4. Labour distribution of miscanthus cultivation (green and brown harvest regime) compared with a typical conventional annual crop rotation with cereals, maize and intermediate crops (calculations based on KTBL, 2019 [48]). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

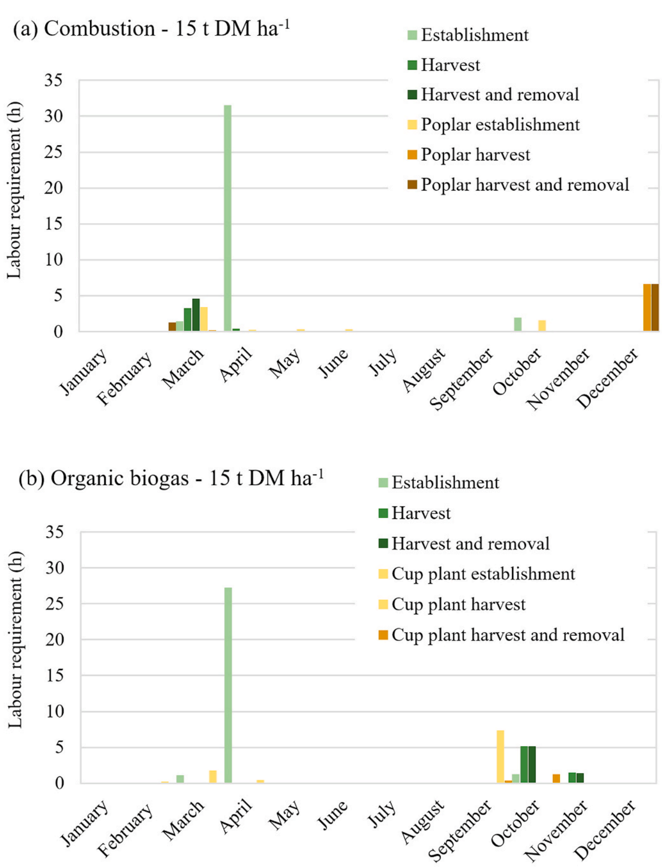

Fig. 5. Annual labour peak distribution (h ha^{-1}) of the rhizome-based miscanthus utilisation pathway (a) combustion compared with a poplar short rotation coppice and (b) biogas compared with cup plant; both on a 10-ha cropping area with a 15t DM ha^{-1} yield from establishment to removal (calculations based on KTBL (2019) [48].

opportunity. The nutrient-rich compost from the animal bedding material can be used as organic fertilizer on the farm or sold. However, the quantities of dedusted miscanthus chips purchased will be much smaller than those for the bioenergy pathways due to the small sales market for bedding material.

Biogas production is also a potentially profitable utilisation pathway, although the miscanthus selling prices assumed here may have been overestimated, as those of maize were taken as an approximation. Therefore, miscanthus cultivation for biogas production is most lucrative for farms that require a biomass supply for their own biogas plants, where the farmer can make use of greening areas or areas that cannot be used profitably for annual biogas crops, such as maize.

Combustion has the lowest gross margins, but also the lowest labour input.

Thus, the most favourable utilisation pathway depends on the individual situation of the farm: If farmers have the (labour) capacity and the appropriate machinery, animal bedding can be recommended as the utilisation pathway with the highest gross margins. However, if labour and time is limited, in particular during the vegetation period of other (annual) crops, the combustion pathway can be most favourable as it balances out work peaks. If farmers have the opportunity to use or sell miscanthus biomass for anaerobic digestion, this pathway is to be recommended, as it allows high gross margins and requires less labour effort than animal bedding.

This study illustrated that larger field sizes lead to economies of scale and thus lower production costs. However, it showed that miscanthus cultivation on smaller field sizes of 1 ha can also provide satisfactory gross margins. These are most likely to be found on riversides or marginal lands (for example awkwardly shaped fields). Miscanthus cultivation on such areas provides a lucrative utilisation option with low labour and time demands, as establishment is only required once for a harvest over several years. For the selection of the cultivation area the location specific opportunity costs should be taken into account in addition to biophysical growing conditions. Further, the perennial nature of the cropping system provides additional services. Soil erosion and nutrient run-off can be reduced and thus water and soil quality secured. The annual leave fall recirculates nutrients within the cropping system and leads to carbon sequestration in the soil. As plant protection and fertilizer application is forbidden on a 5-m buffer strip alongside waterbodies, cultivating miscanthus on such areas would be one way of using them efficiently. Farmers can support the ecosystem service provision while might being able to achieve high gross margins, as shown in the organic biogas utilisation pathway.

This study underlines the advantages of miscanthus cultivation: (i) It is an economically viable crop with multiple feasible utilisation options; (ii) Miscanthus grown on marginal land areas (including buffer strips, awkwardly fields, slopes, heavy clay soils) can render such areas profitable with comparably low labour requirements; (iii) When grown as a commercial crop on larger fields, it can help balance out or even reduce work peaks; (iv) The perennial nature of the crop provides multiple ecosystem services, directly relevant for farming and environmental conservation including carbon storage, soil fertility improvement, erosion reduction and prevention of nutrient leaching into water bodies.

Miscanthus production is suited to existing farming practices and helps increase economic efficiency, farm flexibility and sustainability. Thus, its optimal integration into farming practice can promote the sustainable intensification of industrial crop cultivation for the growing bioeconomy. Miscanthus cultivation provides biomass for a number of utilisation pathways and, with its low-demanding and perennial nature, at the same time benefits soil and water quality.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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